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13. ABSTRACT (Maximum 200 words)

As MOSFET scaling matures in the next 10-20 years, "quantum" semiconductor devices are expected to enable the continued increase in the performance of electronic systems. These devices depend on the "coherent" transport of electrons and/or on the properties of single electrons. Because electrons scatter, causing them to lose coherency, and because the effect of single charge is increased in small volumes, nanotechnology is required to fabricate such devices. In this work, we examined fundamental and practical issues associated with quantum devices. Highlights of the work are the theoretical and experimental confirmation of the increase of the coherence time of electrons confined to small volume, the development of high throughput nanomanufacturing tools, and the use of these tools to create single electron memory devices operating at room

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Enclosure 3

Final Report

MURI: Operation and Fabrication of Single Electron and Coherent Nanoscale Semiconductor Devices

Army Research Office Grant: DAA655-98-1-0270

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Table of Contents

Abstract

As MOSFET scaling matures in the next 10-20 years, "quantum" semiconductor devices are expected to enable the continued increase in the performance of electronic systems. These devices depend on the "coherent" transport of electrons and/or on the properties of single electrons. Because electrons scatter, causing them to lose coherency, and because the effect of single charge is increased in small volumes, nanotechnology is required to fabricate such devices. In this work, we examined fundamental and practical issues associated with quantum devices. Highlights of the work are the theoretical and experimental confirmation of the increase of the coherence time of electrons confined to small volume, the development of high throughput nanomanufacturing tools, and the use of these tools to create single electron memory devices operating at room temperature.

I. Problem Studied and Highlights of Results

Introduction

As the end of the conventional "Moore's Law" scaling of electronic devices is in sight, there is a great expectation that future quantum-based electronic devices will enable a continued increase in the performance of electronic systems. This program addressed three major issues associated with such devices. First, the fundamental physics in such devices was addressed from both an experimental and theoretical point of view. The points addressed are the increase of coherence time, a critical figure of merit in quantum devices, by several orders of magnitude by confinement of the carrier into a very small location, the proof of principle that devices can be made insensitive to fabrication defects and trapped charges, and the observation of transport dependent on spin-coherence.

Second, technologies for the fabrication of quantum devices were investigated. Major issues are creating ultrasmall structures, and fabrication methods that do not introduce damage or defects into the structures. A low-energy AFM-based lithography was developed for nano patterning both III-V and Si-based materials with linewidths under 20 nm, and successfully applied to quantum devices in both materials. The technology for metal contacts with ultra-small gaps between them was also developed by nanoimprint lithography, with gaps as small as 5-10 nm.

Third, quantum devices have been developed in silicon-based materials, which one expects will be used for future large-scale application. The fundamental physics of silicon-based quantum dots was probed thoroughly for the first time, and novel magnetic and spin effects were discovered. Nanoimprint lithography, a potential high throughput nano-patterning technique, was used to demonstrate single-electron devices in silicon which operated at room temperature. Finally, for large-scale systems, a Si/SiGe structure was developed for the first time to avoid the ubiquitous Si/SiO_2 interface states from which existing Si devices suffer, and demonstrated in extremely repeatable coulomb blockade devices.

Note references for Sec. I are given in corresponding section in Section III, "Details"

I.A. Coherent Transport and Devices

I.A.1. Theory and experimental confirmation of Confinement-Enhanced Coherence
Dephasing is a critical issue which affects both classes of quantum devices – coherent and single electron devices. In devices based on coherent transport or coherent states (as in a dot), the avoidance of dephasing is central to the device. In single electron devices, dephasing and many-body phenomena will also affect transport in and out of the central dot structures. In this project, we have established the theorectical basis and quantitatively experimentally confirmed the effect of confinement-enhanced coherence. This is a very important idea that roughly states that the decoherence of electrons in a quantum dot *vanishes* at temperatures approaching the quantum level spacing, i.e. the coherence time approaches infinity This does not occur in open quantum dots. This is a most important result which has great positive significance for the viability of future quantum devices.

I.A.2. Spin-orbit transport and observation of Berry's phase
We explored the important role of the spin-orbit interaction in the operation of nanoscale semiconductor devices. This interaction is one of the key elements in "spintronic" devices where the carrier spin and its manipulation are utilized for the device operation. In our work, we first demonstrated the tunability of the spin-orbit interaction in two-dimensional (2D) hole systems confined to GaAs quantum wells via the application of gate electrodes. We then studied the phase coherent spin transport in 2D hole systems by fabricating Aharonov-Bohm rings and measuring resistance oscillations as a function of magnetic field. The data demonstrated signatures of phase coherent transport, but also pointed to the very fragile nature of the phase coherence in this system. The work has been highlighted in several articles in the scientific press.

I.A.3. Defect-Insensitive Coherent Devices and Time Resolved Transport
In principle, coherent devices should be sensitive to random trapped charges (as scattering site), a possible enormous practical difficulty. Using Aharonov-Bohm rings to measure the quantum mechanical interference of electrons, we were able to show that the oscillations (as a function of the magnetic field through the ring) of the reflection off an Aharonov-Bohm is insensitive to slow changes in the potentials applied to the different arms. This shows a path towards the design of devices which are insensitive to such random potentials and random trapped charges. In the second part of the work, we demonstrated the first time-resolved measurements of 2-dimensional electron transport on a picosecond time scale.

I.B. Nanopatterning technology

I.B.1. AFM-based low-energy nanopatterning for quantum effect devices

To avoid damage from high energy patterning processes (such as radiation damage from e-beam lithography and from reactive ion etching), we have developed the technique of AFM-based lithography. An AFM tip with an applied voltage is used to write oxidized lines on a surface, which can then be transferred to an underlying layer by wet etching. The technique has been used to draw 20-nm features and to make quantum devices in both GaAs and Si/SiGe [1,2,3]. The Si/SiGe patterning was combined with a novel epitaxial growth to avoid surface states on the surface of a quantum dot, and then to make a silicon-based single-hole transistor free of spurious effects in other devices attributed to defects at the Si/SiO_2 interface.

I.B.2. Nano-contacts for ultra-small (<10 nm) devices

We developed fabrication processes for producing nano-contacts for ultra-small (< 10 nm devices) using nanoimprint lithography (NIL). Ultra-small single molecule devices have great potential for next generation memories, transistors, and sensors due to their intrinsic small size, customizable composition, and ability to "self-assemble". To this end, we have been exploring guided self-assembly of alkanethiol and DNA molecules in

contacts fabricated using NIL, a fully parallel, high throughput, sub-10 nm resolution lithography [1]. We have explored two different types of nano-contact strategies. First, we fabricated Au contacts separated by a distance as little as 5 nm in which a single molecule can be captured. Second, we fabricated a "sandwich" structure whereby a monolayer of molecules is grown on a contact, and then the second contact patterned on top of the monolayer.

I.C. Silicon-based quantum devices

I. .C.1. First Si-based single-electron device without Si surface or Si/SiO$_2$ interface states

While silicon-based single-electron devices are recognized as those most likely for large-scale implementation, to date quantum dots based on silicon have had either unpassivated surfaces or surfaces passivated with SiO$_2$. However, both bare surfaces and Si/SiO2 have defect states, which are known to interfere with the operation of quantum effect devices. To overcome this approach, SiGe quantum dots have been completely surrounded by pseudomorphic epitaxial silicon, so that all atoms at the surface of the dot have bonds with their neighboring atoms in the silicon cladding. Si-based coulomb-blockade devices which with extremely narrow linewidth and which were very stable, both indications of a lack of interface states, were demonstrated with this approach.

I.C.2. Single-electron memory room-temperature devices from nanoimprint lithography
We report the design, fabrication, and characterization of room-temperature Si single-electron memories using nanoimprint lithography (NIL). The devices consist of a narrow channel metal-oxide-semiconductor field-effect transistor and a sub-10-nm storage dot, which is located between the channel and the gate. The memories operate at room temperature by charging and discharging one electron in or out of the dot. The charge retention time is up to two days. NIL is shown to be tailored for nanodevice fabrication. By using NIL as a nanolithography tool, the single-electron memory is more feasible for mass production

I.C.3. First in-depth study of physics of quantum effects in silicon dots
While silicon-dot based devices are recognized as the most likely for future quantum device applications, previously there had been little fundamental understanding of these dots. Highlights of the results include:

– energy spectrum of a few (0-30) electron quantum dot
– novel (presumably valley degeneracy related) Kondo effect in Si QD
– interaction-driven spontaneous polarization and discovery of spin blockade
– inelastic co-tunneling in the limit of strong coupling to the leads
– developed a new method to determine coherence of the transport using double-dot devices
– many-body effects and wavefunction reconstruction in Si QD
– analysis of multi-dot behavior in Si/SiO$_2$ nanodevices

II. Army/MURI Interaction

Over the past six years, we have collaborated (through Prof. Daniel Tsui) with Dr. K. K. Choi at the Army Research Laboratory, Adelphi, Maryland. on quantum well infrared detectors. Specific issues of interest are the energy filtering of hot carriers resulting from the high fields in the detector, which results in an increased signal/noise by suppressing dark current, and second, metal patterning leading to resonances to increase the coupling efficiency of light to the desired transitions in the optical well.

We have developed a collaborative relationship with the R&D unit at US Army Piccatiny Arsenal in NJ. We have engaged in information exchanges through in-person meetings at Princeton and at Piccatiny Arsenal as well as communicated through a variety of modes our research interests, and obtained Piccatiny's advice on their needs, interests and priorities. The center of the work is on nanotechnology and nanofluidics. The key faculty involved in this effort include Profs. Sandra Troian, Jim Sturm and Sigurd Wagner. We have also executed an Educational Partnership with Piccatiny Arsenal with defined areas of focus for research educational programs of mutual interest. On February 27, 2004, Princeton hosted a Piccatiny Technical Progress Workshop to share results from a Nanotechnology BAA with existing university and industry collaborators, and to invite involvement of new companies to promote technology transfer and commercialization.

In 2004, Both Prof.'s Lyon and Chou recently attended a workshop at the Army Research Lab on "Next-Generation Electronics" hosted by the Sensors and Electron Devices Directorate. This was a wide-ranging discussion of possible new directions, including quantum devices, that ARL might consider pursuing. Prof. Lyon also recently served on the external review committe of the NRL Electronics Program (Electronics S&T Division).

III. Details of Results

III.A. Coherent Transport and Devices

III.A.1. Theory and experimental confirmation of Confinement-Enhanced Coherence
The aim of our research within the MURI team was to investigate quantum coherence in *isolated* quantum systems, with an aim of observing confinement-enhanced coherence. Confinement-enhanced coherence is the predicted rapid increase, and in fact divergence, of the quantum coherence time in isolated quantum systems. It cannot be observed by traditional transport methods used to measure coherence times in open mesoscopic systems, and new methods needed to be developed. In Ref. [1], a new method was introduced based on an analog of weak localization in the Coulomb blockade regime. The idea is that wave function symmetry affects the average Coulomb blockade peak height leading to differences between the average peak height at zero and nonzero magnetic fields. The difference only exists in the coherent regime. It was later shown by Beenakker that the difference in average peak-height between broken and unbroken time reversal symmetry can be used to quantitatively determine the energy relaxation rate in nearly-isolated devices. With this technique, Eisenberg, Held and Altshuler [2] used the results of Folk to show that the isolated dot was showing confinement enhanced coherence, with dephasing times of order 100 ns (compared to a few ns in open devices).

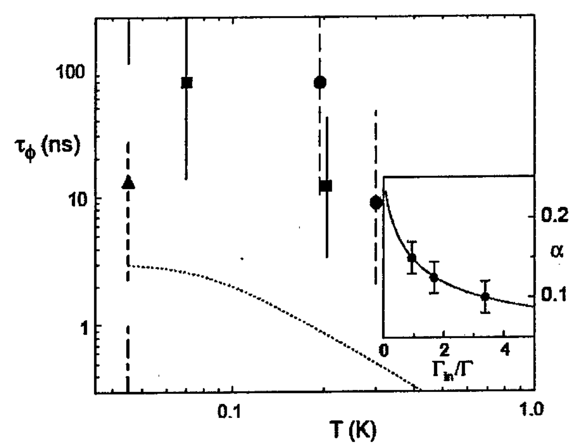


Fig. 1. Extracted dephasing rate for a nearly-isolated quantum dot, based on change in average Coulomb blockade peak height upon breaking time reversal symmetry. The data is from Ref. [1], and the analysis is from Ref. [2].

In subsequent work, two other approaches to measurement of coherence in nearly isolated devices were investigated. The first approach [3] was to couple a quantum dot in the tunneling regime to a single lead, forming a Fano-resonance device. The motivation for this study was a paper by Clerk, *et al.* [4], which predicted that dephasing in arbitrarily isolated dots could be measured from the Fano lineshape (specifically from its visibility—that is, did the minimum conductance in the Fano resonance go to zero). It turned out that the theory did not account for thermal affects and it was not possible to use this set-up to detect confinement-enhanced coherence. On the other hand, with this controlled Fano

device we were able to extend the (noninteracting) Fano theory to a new regime, which we called *Coulomb-modified Fano regime*, where charging effects and Fano interference effects are combined. This paper has been submitted to Physical Review Letters. The second approach was to disconnect conductance altogether and examine charge states via capacitive sensing [5]. This is an approach with very important consequences for mesoscopic physics. With this approach, we are able to measure the charge within a quantum dot with an accuracy of approximately e/100 without transport through the dot. We have incorporated charge sensing into several recent experiments for both spin and charge readout.

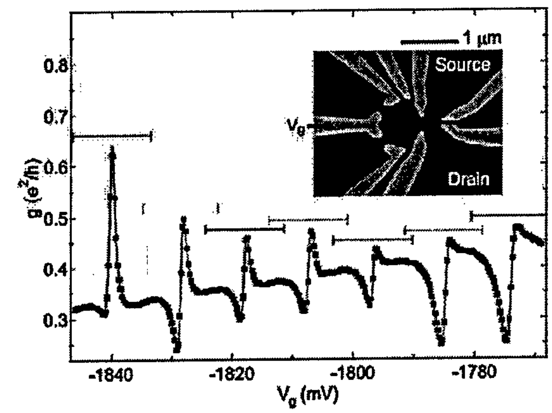


Fig. 2. Fano resonances (data is black dots) in a side-coupled one-channel quantum dot, along with fits based on the Coulomb-modified Fano theory. From Ref. [3]

In Ref. [5], the hybridization of charge between two dots was investigated non-invasively, and was found to be in excellent agreement with a theoretical model developed within the same paper. What about coherence? This first measurement was able to distinguish between thermal smearing of two states (in a double quantum dot) and quantum hybridization. +However, it was not sensitive to coherence in the sense of detecting Rabi oscillations between the two states. This is a much more challenging experiment and will be the subject of future work.

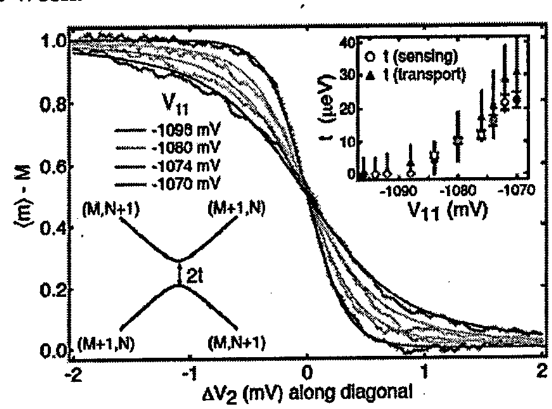


Fig. 3. Noninvasive charge sensing measurement of the average occupancy of the one of a pair of coupled quantum dots, as a function of the energy tilt of this two-level system, for several values of interdot coupling. The inset shows a comparison of interdot coupling

energy measured by this sensing method compared to values extracted from (less accurate) transport. From Ref. [5].

We also studied theoretically the relevance of tunneling two-level systems (TLS) for electron dephasing in infinite systems. We demonstrated that if the concentration of TLS is sufficient to cause the observed dephasing rate, one also should expect quite substantial effects in the specific heat and ultrasound attenuation. In both cases TLS contribution should dominate the electronic one at low enough temperatures. [6]. One of the most striking manifestations of the correlations between particles in quantum liquids is Anderson orthogonality catastrophe. We analyzed the mesoscopic version of this phenomenon that takes place in finite conductors with diffusive disorder. We found that disorder averaged logarithm of the overlap between the ground states before and after adding a static impurity depends nonmonotonically on the disorder. In two dimensions it is proportional to the squared logarithm of the number of electrons. Numerical simulations demonstrate a very broad tail of the distribution of these overlaps. This tail manifests the importance of a few-level statistics at the Fermi energy.

III.A.2.1.Tunable spin-orbit interaction and spin-splitting in GaAs 2D hole systems

An important and interesting characteristic of the 2D holes in (311)*A* GaAs/AlGaAs heterostructures is their rather large "spin-splitting" in the absence of an applied magnetic field. The splitting is a result of strong spin-orbit interaction and the lack of inversion symmetry in both the host (GaAs) crystal and the confinement potential. In our work, we used gates on the front and/or back sides of the wafer, and showed that the spin-orbit interaction and therefore the spin-splitting can be tuned (see Fig. 1) [7]. The results were in good agreement with the theoretical calculations, performed by our collaborator, Dr. Roland Winkler of the University of Erlangen. This agreement is remarkable, particularly since the calculations involve essentially no fitting parameters. Our results also revealed several surprises. For example, we found that in a system with spin-orbit interaction, the frequencies of the Shubnikov – de Haas oscillations are not simply related to the populations of the spin-subband densities as is generally assumed [8]. We have also observed another unexpected behavior both experimentally and theoretically. Normally, the inversion asymmetry-induced Rashba spin-splitting in 2D systems at zero magnetic field is proportional to the electric field that characterizes the inversion asymmetry of the confining potential. Our results [9,10] demonstrated, both experimentally and theoretically, that 2D heavy hole systems in accumulation-layer-like single heterojunctions show the opposite behavior; i.e., a decreasing but non-zero electric field results in an *increasing* Rashba coefficient.

Our results have had implications for another interesting problem of current interest, namely whether or not a true metallic state can exist at zero-magnetic-field. We made various measurements of the transport properties of GaAs 2D hole systems grown on (311)*A* substrates. We took data both at zero magnetic field, and in the presence of a parallel field [7,10-14]. The results indicate that the metallic temperature dependence observed at finite temperatures is likely linked to the scattering of holes between the two spin subbands [7,12]. Our data taken with a magnetic field applied parallel to the 2D plane corroborate this conclusion [11,13].

III.A.2.2 Phase-coherent spin transport in a 2D system with spin-orbit interaction

In this exciting project, we studied the role of spin-orbit interaction in Aharonov-Bohm oscillations, with the goal of utilizing this interaction to realize a "spin interference device". In our work, we measured Aharonov-Bohm oscillations in rings made from (311)*A* GaAs 2D holes, a system in which our previous studies had established spin-orbit interaction and its tunability via gate bias. Figure 2 shows a micrograph of the ring structure and an example of the observed A-B oscillations [15]. Also shown is the Fourier transform (FT) spectrum of the oscillations. The oscillations show a clear "beating" that manifests in the FT spectrum as extra structure on the sides of the main peak whose frequency corresponds to the magnetic flux enclosed by the ring (~170 Tesla^{-1} in Fig. 2). The shape of the extra structure, namely, the positions, amplitudes, and number of the side-peaks observed in the FT spectrum, evolve with the range the magnetic field over which the spectra are taken. We also did simulations based on a simple model that takes into account the spin Berry phase, a geometrical phase that the carrier acquires when it goes

around a closed path, in a system with spin-orbit interaction. Comparison of the data with the results of simulations suggests that the origin of the extra structure is the Berry phase. This is very exciting! Berry's phase is very fundamental and yet mysterious; it has seldom been observed in a solid-state electronic system. Our work has already attracted much attention and was featured in the "Physics Portal" of the *Nature* journal on March 26, 2002, in the Virtual Journal of Nanoscale Science & Technology on April 12, 2002, and in the "Science's Compass" section of the *Science* magazine on September 6, 2002 [J. Anandan, *Science* **297**, 1656 (2002)].

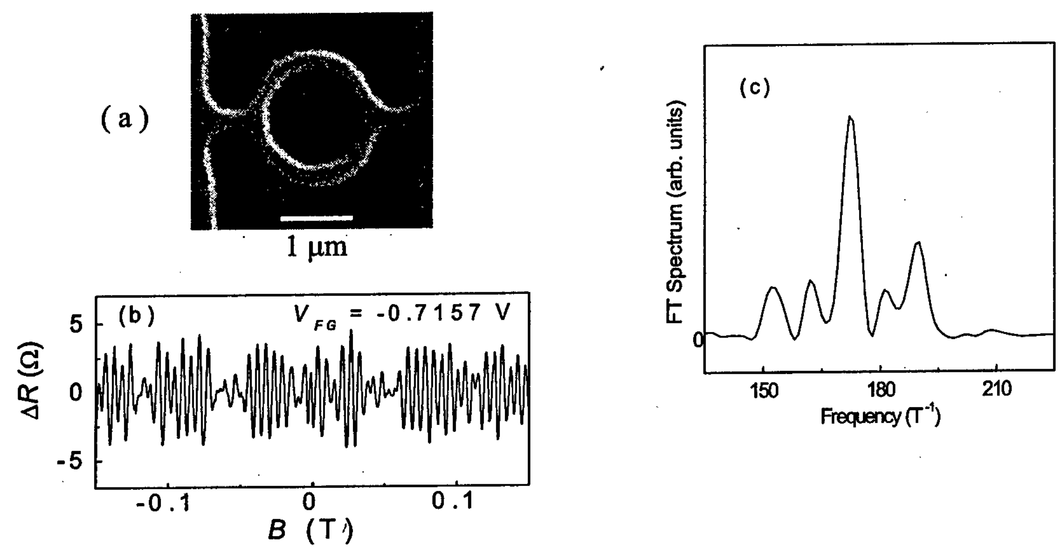


Fig. 2 (a) Scanning electron microscope image of the ring structure used for measurements of the A-B oscillations. (b) Example of measured A-B oscillations in a GaAs 2D holes system. The beating in the oscillations is attributed to the spin-orbit interaction and the spin Berry phase, and manifests itself as side peaks in the Fourier transform spectrum of the oscillations, as shown in (c).

III.A.3. Defect-Insensitive Coherent Devices and Time Resolved Transport

III.A.3.1. Reflection and Transmission from Aharonov-Bohm Rings

We obtained, for the first time we believe, clear data showing simultaneous reflection and transmission from an Aharonov-Bohm (A-B) ring[16]. The device is shown in Fig 1. The light areas are metallic gates (labeled G_n) and the dark areas are the underlying GaAs. The 2D electrons are depleted beneath the gates, leaving the ring in the center connected to the left and right contacts through narrow channels. Gates G_2 and G_3 must be positioned close to the ends of the channel, splitting the electron signal into transmission and reflection and measured as V and V as indicated in the figure. The data obtained with this device is shown in Fig. 2, with transmission results in the upper panel and the reflected electron signal in the lower one. The voltage oscillations with magnetic field are on the left, and their Fourier transforms are on the night. The reflection signal has a period (with respect to the magnetic flux through the ring) that is one half of the transmission signal because the electron goes twice as far around the ring. Then, with a DC voltage applied to a gate (G_1) on one arm of the ring, we can mimic the effect of an extraneous charge – a defect – in the vicinity of the device. The phase of the oscillations in the transmission as a function of applied magnetic field shifts with gate voltage, but the reflected signal shows no such phase shift. This effect demonstrates the principle of a switch which is insensitive to defects (charges) in its vicinity.

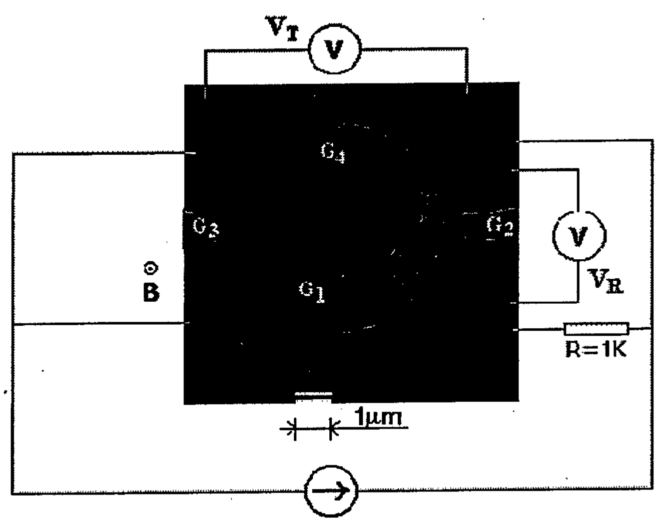


Figure 1. Electron micrograph of device used to simultaneously measure electron reflection and transmission from an Aharouou- Bohm ring. The light areas are metallic gates for locally depleting the 2D electrons.

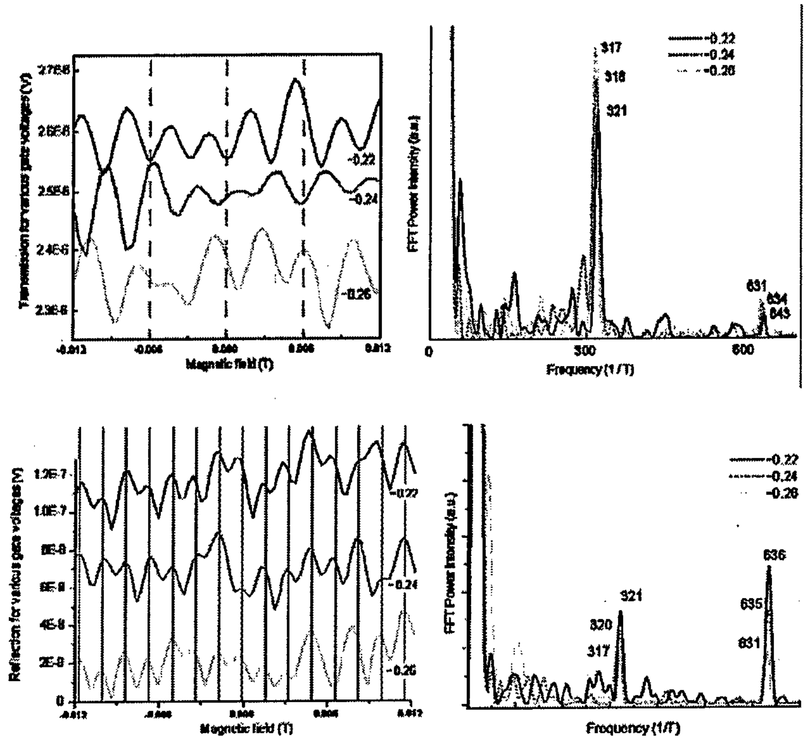


Figure 2. Transmission (upper) and reflection (lower) signals from the device shown in Fig. 1. The three curves in each figure correspond to different voltages applied to gate G_1.

III.A.3.2. Picosecond Time-Resolved 2D Electron Transport

One of the most powerful ways to utilized quantum interference in devices is in the time domain, as is done with optical pulses in fiber optic systems. However, previous attempts to time-resolve electron transport in high-mobility 2D electron systems with the necessary resolution (a few picoseconds) had been unsuccessful. First, we showed that we could use picosecond electrical pulses, excited optically on coplanar waveguides, to time-resolved cyclotron resonance oscillations [2]. More recently, we have successfully demonstrated time-resolved transport, as is shown in Fig. 3 [18].

We have used a magnetic focusing structure to allow us to vary the transmission with a magnetic field and thereby distinguish our signal from electrical pickup. The sample is shown on the left side of the figure. The upper two images are micrographs of the device. The one on the left shows the overall structure, and the indium pads used to flip-chip bond the device to the waveguide structure shown in the bottom figure. The right-hand electron micrograph shows the electron focusing structure. The lighter regions in the image are where the AlGaAs/GaAs has been etched slightly to deplete the 2D electrons. Electrons are emitted from the left (E) through a point contact, and travel ballistically through the base (B). If a perpendicular magnetic field is applied, the electrons' paths are curved, as shown schematically by the white curves in the image. For particular magnetic fields, the electrons' paths lead to the collector point-contact (C). For these field values, a peak in the

collector current is seen. For other fields, the collector current is lower. Thus, one expects oscillations in current with B-field, but only for one sign of the field.

The data on the right side of Fig. 3 shows the characteristic oscillations with field for magnetic focusing in the traces taken with time delays of 50-90 ps. The data shown here

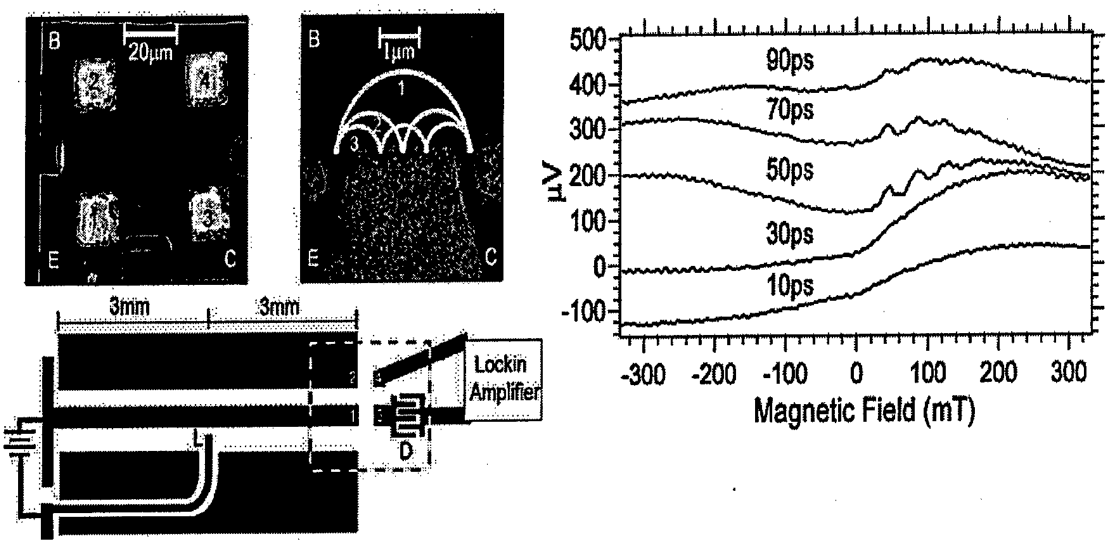


Figure 3. The lower figure on the left is an overview of the coplanar waveguide structure used to generate and transport the picosecond electrical pulses to the device (shown schematically as the dashed square). The interdigitated structure at the right acts as a sampling switch to time resolve the signal. The upper two micrographs show the actual device, a low-resolution view on the right, and an electron micrograph showing (schematically) electron paths from the emitter point contact to the collector contact in the magnetic focusing structure. The time-resolved transport through the device as a function of magnetic field for different time delays is shown at the right.

are unprocessed, and the variations between the traces at different delays reflects the magnitude of the pickup. Interestingly, the time delay from when the picosecond electrical pulse drives electrons out of the emitter to when they arrive at the collector (the peak current is at about 50 ps, as seen from the figure) is longer than expected. Using the Fermi velocity for our electron density one expects a delay that's about one half of what we measure. The new techniques we have developed for these measurements can be expected to lead to the further discovery interesting phenomena. We are investigating some of these possibilities.

III.B. Nanopatterning technology

III.B.1. AFM-based low-energy nanopatterning for quantum effect devices

To avoid potential defect states created by high energy patterning (e.g. electron beam radiation or damage from plasma etching), we have developed the method of Atomic Force Microscope (AFM) oxidation to pattern semiconductor surfaces, and wet etching methods to transfer the patterns into GaAs, Si, and SiGe devices. The method has been used (Sec III.C.1) to create single electron transistors in SiGe quantum dots with extremely stable performance.

When an AFM tip with an applied voltage is moved over a surface, water vapor adsorbed on the surface leads to anodic oxidation of the surface. This direct oxidation can be used to consume dopants in the supply layer of a 2-D gas (leading to a pattern in a 2-D gas structure or can be transferred to underlying layers by wet etching). Thus 2-D conducting layers can be "cut" and patterned into separate regions. Because of the narrowness of the insulating lines between the conducting regions, the conducting regions can be used as lateral gates to modulate the potential of adjacent regions. Linewidths range from under 20 to over 50 nm depending on scan speed and voltage, and the oxidation depth is on the order of nm. Typical voltages are on the order of 10-30 V. Fig. 1 shows a schematic of the structure and initial results on a silicon surface [19].

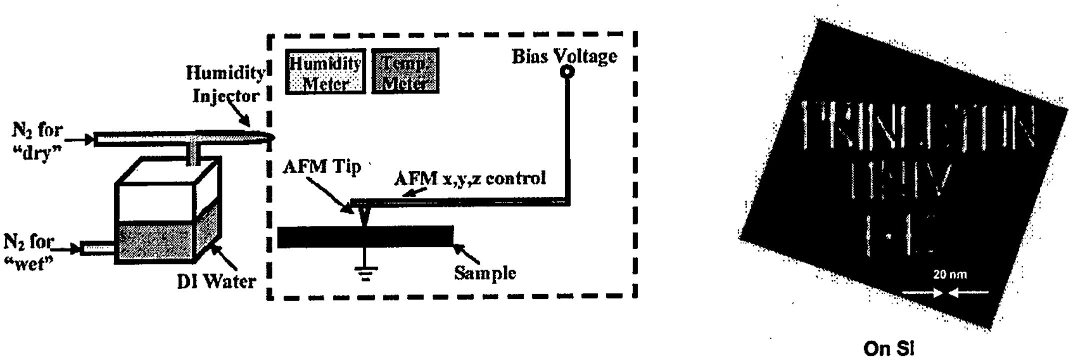


Fig. 1. Schematic diagram of AFM oxidation and initial demonstration on silicon.

The feasibility of the method was demonstrated through the writing of complex device patterns on both Si and GaAs surfaces (Fig. 2). The pattern of Fig. 2(a) shows a structure for patterning a 2-D conducting layer into a single-electron transistor, with separate side gates (G1 and G2) for modulating the central dot potential and side gates (PC1 and PC2) for modulating the barrier potential between the dot and source/drain. In this structure, the oxidized pattern has been removed by selective etching with HF. The structure of 2(b) shows a narrow line isolated by AFM oxidation. Applying a potential to the lateral side gates next to the line can be used to adjust the potential of the central line, leading to its full depletion [20].

Because the oxidation depth self-limits after ~4 nm, one can not directly pattern thicker layers. To pattern thicker structures, we then adopted a 2-step transfer method [21]. For example, if one wants to pattern a 8-nm SiGe layer, one can first oxidize a thin (2 nm) Si layer on top of it by AFM oxidation. The oxide layer can then be removed selectively by HF, exposing the SiGe surface. The SiGe in turn can then be etched by another selective etchant, which removes SiGe and not Si. This method has been used to create Si-Ge/Si single hole devices with extremely stable performance [22] (See Sec III.C.1).

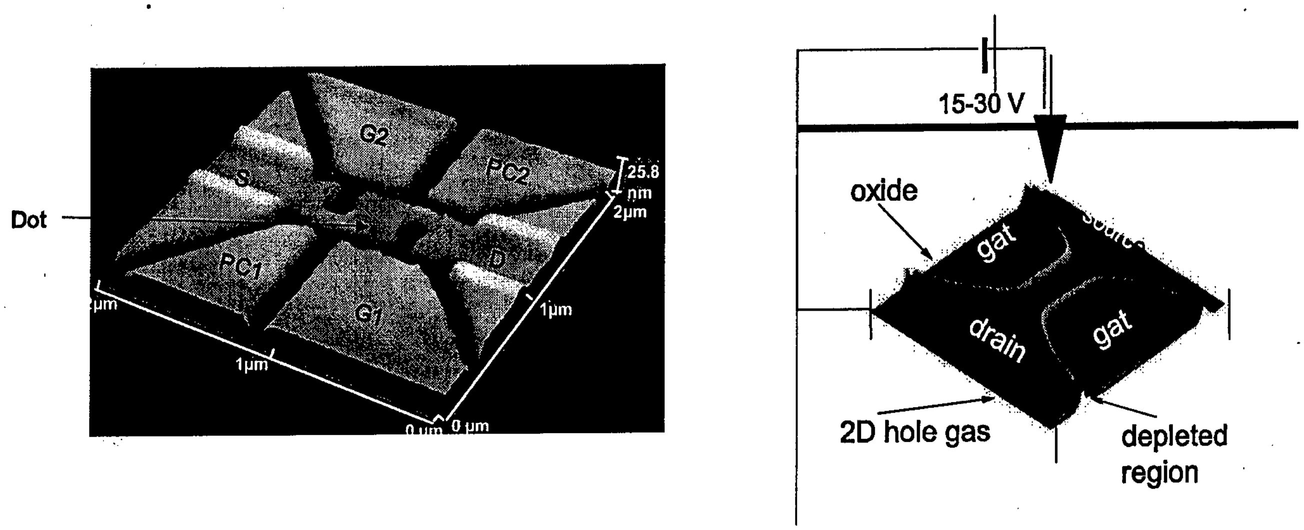


Fig. 2. Patterned devices in (a) SI/SiGe and (b) GaAs/AlGaAs.

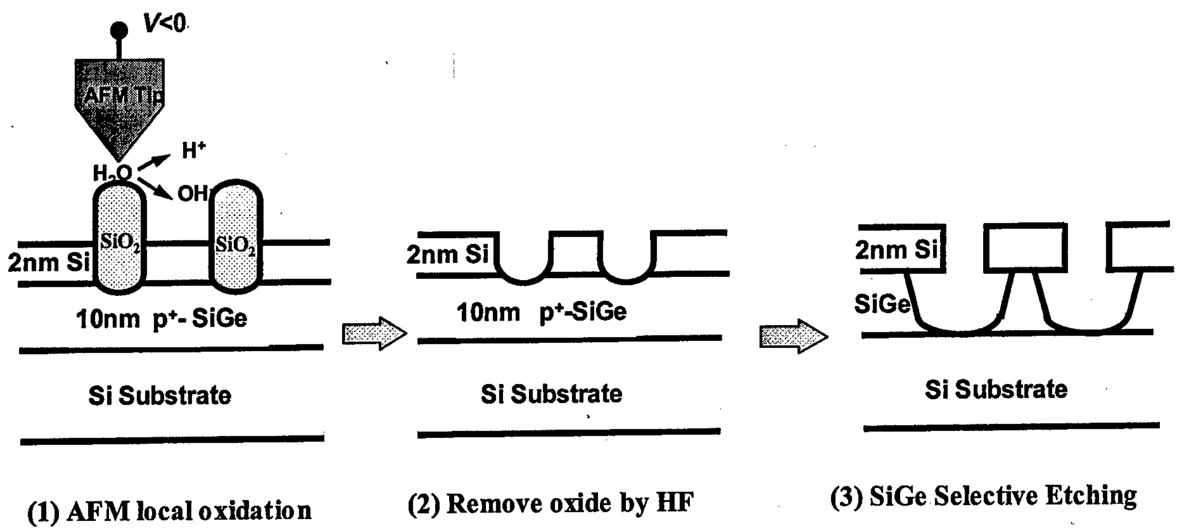


Fig. 3. Two step method for pattern transfer to thick layers (~10 nm) after AFM oxidation.

III.B.2. Nano-contacts for ultra-small (<10 nm) devices

The limits of device shrinking have been explored by creating contacts with ultra-small gaps (< 10 nm) between them. The long range goal is to use them to self-assemble devices by trapping single molecules between the two contacts. A device composed of a single molecule trapped between two metallic contacts pushes the limit of electronic device scaling. Many questions regarding the stability, repeatability, and performance of such a device remain unanswered due to the difficulty of fabricating the necessary metallic contacts in which the single molecule will self-assembly between, and be electrically probed by. We have developed a fully parallel process of fabricating contacts on a microchip using NIL, a lithography with the proven resolution to reach sub 10-nm features. Using NIL, gold contacts, separated by as little 5 nm, were fabricated on a quartz substrate [23] (see Fig. 1). With this capability to reliably mass-produce such contacts, the science of guided molecular self-assembly and single molecule conductivity can be efficiently explored.

While direct fabrication of nano-contacts with ultra-high resolution NIL lithography holds the long-term promise of single-molecule devices, we also explored the more immediate route of electrically probing a monolayer of single-molecules. Using NIL and shadow evaporation, microchips were produced where-by a SAM could be grown and its conductivity studied with a fully parallel fabrication process. Here, the SAM was grown on a bottom contact, and a top contact was evaporated over the SAM. The physical dimension of the top contact was reduced to an area as small as 40 nm x 40 nm to reduce the risk of electrical shorts (Fig. 2a). Using this process, the electrical characteristics of an octadecanethiol (C-18) SAM were studied (Fig 2b) [24].

Figures on next page

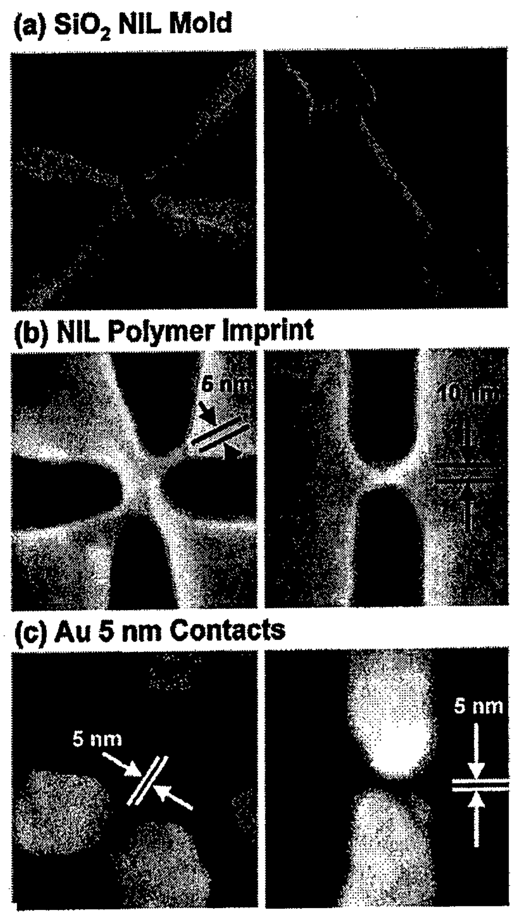


Fig. 1: (a) A scanning electron microscope (SEM) image of a nanoimprint lithography (NIL) SiO2 mold of nano-contacts patterned by electron beam lithography (EBL).
(b) Patterned contacts in polymer on a quartz substrate using the NIL mold shown in (a). These patterns were produced with a fully parallel process, and can be reliably reproduced again by the same mold.
(c) Pattern transfer of the polymer imprints shown in (b) to Au to produce guided self-assembly sites for single molecules.

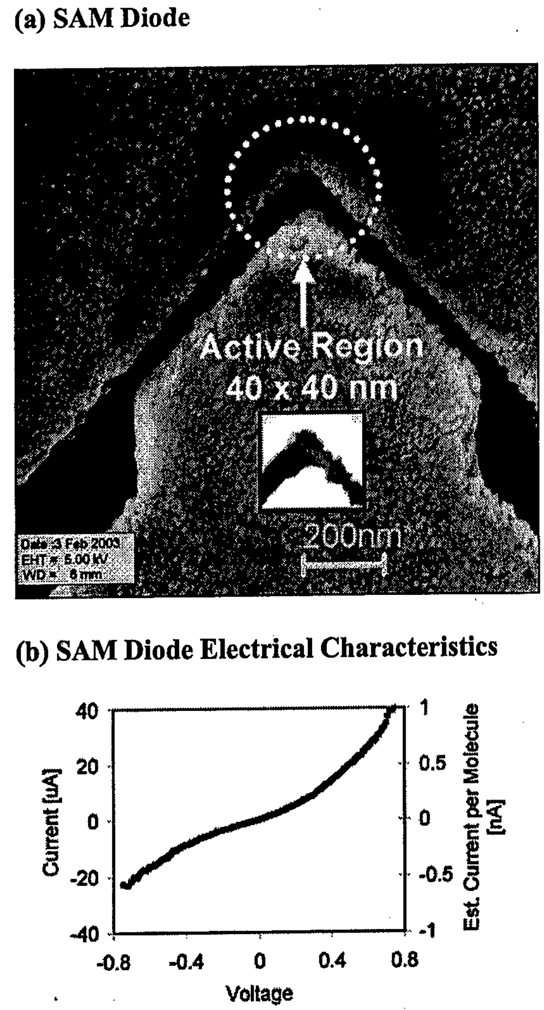
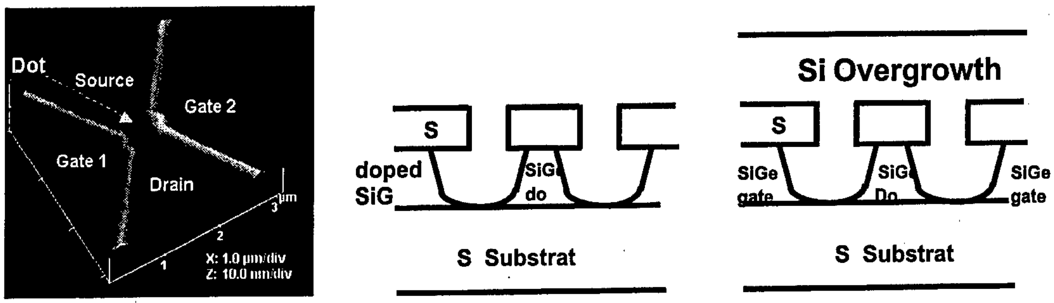


Fig. 2: (a) A scanning electron microscope (SEM) image of a Self-Assembled Monolayer (SAM) diode. The octadecanethiol (C-18) SAM is grown on the bottom Au contact, and then the second Au contact to the SAM is evaporated over top. To reduce the risk of electrical shorts through the C-18 SAM by the Au atoms during evaporation, the active region is minimized to 40 nm x 40 nm.

III.C. Silicon-based quantum devices

III.C.1. First Si-based single-electron device without Si surface or Si/SiO$_2$ interface states



(b.)

(c.)

Fig. 1. (a) AFM image of Si/SiGe quantum dot transistor after AFM oxidation before pattern transfer, (b) cross section after oxide removal and SiGe etching, and (c) dot surface passivation by silicon epitaxial regrowth.

Our earlier work has found that single interface states can greatly interfere with the operation of single-electron devices, and oxide traps can also provide a parallel path for the transport in quantum dot devices in addition to the path through the desired dot [25]. To overcome these limitations, we have developed a device structure in which the patterned dot is not surrounded by SiO$_2$ to confine carriers to the dot, as is done in existing approaches to silicon quantum dots, but rather by a pseudomorphic semiconductor interface. In our experiments a doped SiGe layer was patterned by AFM lithography and wet etching to define the dot structure, source, drain, and side gates in a single conducting p-type layer of SiGe. At low temperature, carriers are confined to the SiGe by the valence band offsets. Thus when the SiGe layer is cut (Fig 1(b)), the side gates are electrically disconnected from the dot, but they can be used to modulate the dot potential. Quantum confinement effects in the narrow gap (<10 nm after etching) between the source (drain) and dot creates a barrier (estimated at 8 meV) between the source (drain) and the dot. Modulating the dot potential brings the dot states into alignment with the source, which then allow current to flow in the device. Because of the coulomb charging energy of the dot, these states are widely separated, leading to current oscillations vs gate voltage (Coulomb blockade)

After patterning, the surface of the dot was bare with many surface states, so that any devices at this step had very broad linewidths (e.g. 100 meV) and the devices varied from scan to scan as carriers moved in and out of traps [26]. We then passivated the dot surfaces with the low-temperature epitaixal regrowth of silicon by chemical vapor deposition [27]. A critical issue was the ability to clean the interface before growth at low temperature (to avoid dopant diffusion) [28]. After regrowth, the single-hole transistors exhibited exceedingly sharp Columb blockade osciallations, with linewdith of ~12 meV

(Fig 2). Most significantly, these devices were repeatable from scan to scan and over multiple temperature cycles (Fig. 2) [29]. The devices also did not exhibit parasitic oscillations due to parasitic current paths related to oxide defect states, as has been observed in earlier SiO_2 passivated dots.

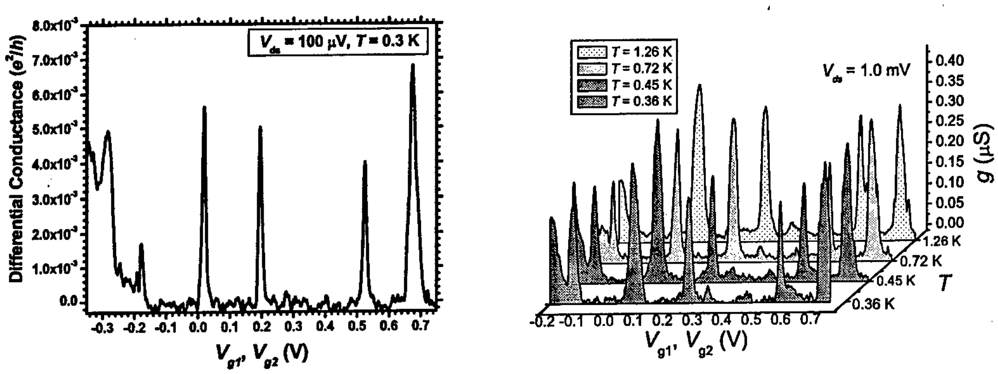
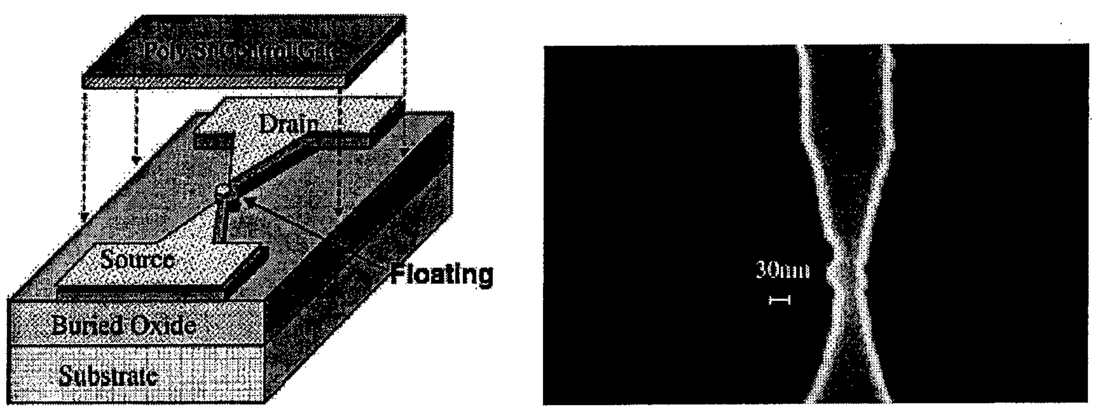


Fig. 2. I-V curves of Si-passivated SiGe quantum dot device of Fig. 1 at low temperature. Devices without passivation had 10X higher linewidth. Also shown are multiple scans vs temperature showing repeatability of peak position.

III.C.2. Single-electron memory room-temperature devices from nanoimprint lithography

As transistors continue to shrink according to Moore's law, single-electron effects are becoming significant in many device structures. The devices utilizing those effects, such as single-electron memory ~SEME!, have a number of attractive and unique properties such as ultra-low-power consumption, ultrahigh density, and quantized threshold voltage shift. SEME working at room temperature is also considered to be a promising candidate for the future generation of flash memories [30]. To make SEME work at room temperature, the storage node must be smaller than 10 nm to guarantee that the quantized energy level spacing is larger than the thermal energy.5 Previously, Si SEME fabricated using electron-beam lithography ~EBL was reported [30] However, EBL has low throughput and high cost, making it impractical for mass production. Other approaches have been used to meet the fabrication challenges, such as using grown Si dots or isolated nanocrystal Si as storage dots. But the multidot nature and the random location of those dots lead to a large fluctuation of the device performance. Therefore, they are unsuitable for large-scale integration.

Here, we report the design, fabrication, and characterization of room-temperature Si single-electron memories fabricated using nanoimprint lithography (NIL) [31]. The devices consist of a narrow channel metal–oxide–semiconductor field effect transistor and a 10-nm-size storage dot embedded between the channel and gate (Fig. 1). The channel layer, which requires sub-10-nm resolution, is defined using NIL, and the floating dot is formed and self-aligned with the narrowest part of the channel to give the stored electron maximum screening ability, and no additional lithography is needed for the dot. The memory operating at room temperature by charging a single electron into or out of the storage dot was observed [32]. NIL is shown to be tailored for nanodevice fabrication. In addition, the high throughput, low cost, and good fidelity of NIL make SEME more feasible for large-scale integration and mass production.



(a) (b)

Fig. 1 (a) Schematic of single-electron memory made by NIL, and (b) imprinted channel and floating poly-Si layer. After gate oxidation, an isolated quantum dot will form in the floating poly, while the channel is still connected. The quantum dot will be the storage node.

There are two major parts in the fabrication process: mold fabrication and device fabrication. In fabricating NIL molds, a master mold was fabricated first using EBL and reactive ion etching ~RIE!. Next, the master mold was duplicated into several Si daughter molds using the NIL process. Then, we oxidized each daughter mold at 850 °C in dry O2 and etched SiO2 in HF to shrink the mold feature size. The oxidation and etching process may be repeated to achieve the required feature sizes. The mold is used in the NIL process to define the channel layer. The device fabrication began with a silicon-on-insulator substrate, and the top Si layer was thinned to 35 nm thick. First, a 2.4-nm-thick tunneling oxide was thermally grown in diluted O2 , and a 13 nm polysilicon was deposited by low-pressure chemical vapor deposition. Second, the Si layer and the polysilicon layer were patterned using NIL and RIE etching. Figure 2 shows a scanning electron microscope image of the patterned channel and floating polylayer. Third, a 13.6 nm gate oxide was thermally grown at 850 °C in dry O2, and followed by a 33 nm SiO2 plasma enhanced chemical vapor deposition. The samples were annealed at 850 °C in N2 to improve the SiO2 quality. Finally, a 3- mm-long polysilicon gate that covered the floating dot and part of the channel was deposited and patterned. After source/drain implantation, dopant activation, final contact, and sintering, the memories were fabricated. Note that during gate oxidation, since SiO2 grows faster in the thin poly-Si layer, the two ''necks'' of the poly-Si layer were totally oxidized, leaving an isolated quantum dot formed in the floating poly-Si layer, while the underneath channel was still continuous. In this way, the floating dot was formed and self-aligned with the narrowest part of the channel.

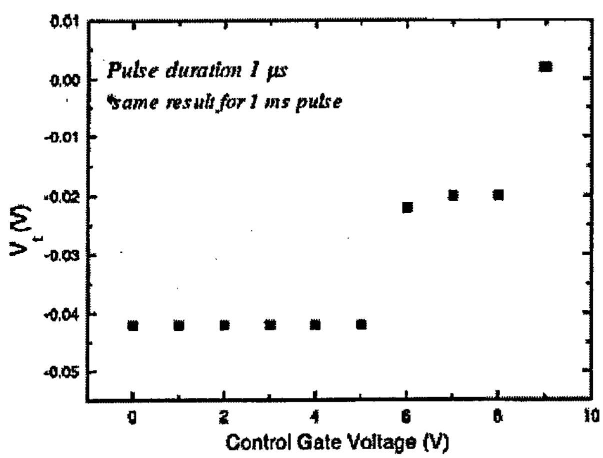


Fig. 3. Threshold voltage of one single-electron memory vs the pulse voltage applied to the control gate before the measurements. The threshold voltage shifted two steps at 6 and 9 V. The shift of each step is about 22 mV. Varying the pulse length from 1 ms to 1 ms has no effect on the measurements. One more electron was charged into the storage node at each threshold voltage shift step.

The devices were characterized at room temperature using a two-step process. First, a voltage pulse was applied to the control gate while the source was grounded and the drain held at a 50 mV bias. Second, the drain current was measured as a function of control gate voltage ($I-V$). A simple switch circuit was used to allow the measurement within 2 s after the charging process. The devices demonstrated a single-electron memory effect at room temperature. As shown in Fig. 3, when the charging voltage varies continuously from 1 to 9 V, the threshold voltage shifted discretely with an increment of 22 mV at 6 and 9 V. The charging of the dot seems to be independent of the charging time, when the charging pulse length varied from 1 ms to 1 ms. The discrete increase in the threshold voltage indicates a single-electron charging into the floating dot at 6 V and two electrons at 9 V, respectively.

Due to the Coulomb blockade, after one electron is charged into the floating dot, the next electron will need a higher charging voltage to conquer the additional Coulomb energy. After each additional electron is charged, the threshold voltage would shift a certain amount due to the screening of the electron. This led to the discrete threshold voltage shift, a staircase relationship between the charging voltage.

We did not observe any quantized or charging-time-independent threshold voltage between the floating dot and the control gate, and Ccg the capacitance between the channel and the control gate. In our devices, Ccg is much larger than Cfg. The Ccg can be estimated from the single-electron Debye screening length and the device dimension. The calculated values, Ccg at 5.9 aF and e/Ccg at 27 mV, are consistent with the experiment. For the devices we measured, the threshold shifts spread from 18 to 23 mV. The variation was due to the feature size variation on the mold. The mold was made by EBL, and we intentionally varied the doses for different sites on the mold. The total capacitance of the dot is about 0.7 aF and is calculated from the size of the floating dot and a tunneling oxide thickness of 2.4 nm. That makes the Coulomb blockage energy spacing, i.e., $e2/C$total, about 0.2 eV. It is much larger than the thermal energy at room temperature ~26 meV, which is why the memory works at room temperature.

III.C.3. First in-depth study of physics of quantum effects in silicon dots (and still the most thorough)

Systematic and rigorous studies of ultra small (~100-200 Å) three-dimensional Si quantum dots were performed. We were able to realize, for the first time, a few-electron Si quantum dot, where the number of electrons can be adjusted between 0 and 30 by electrostatic gating. Our dots have a unique set of parameters, such as very strong confinement, valley degeneracy, luck of rotational symmetry and vanishingly small spin-orbit coupling, which are very different from the conventionally studied GaAs dots, and a remarkable number of new phenomena was observed and investigated for the first time. To name a few, we were able to determine spin configuration of a few-electron dot by directly measuring Zeeman shift of energy levels [33] (see figure), deduce spin of the tunneling electron [33], drive a dot with a fixed number of electrons from singlet to triplet to fully spin polarized state [33] (see figure), observe ``spin blockade", when a single mismatched spin blocks macroscopic charge flow [33,34], discovered an unexpected Kondo-like enhancement of current which, as we speculate, is a result of novel Kondo interactions involving valley degeneracy [35], found unexpected and yet unexplained spontaneous magnetic field-induced reconstruction of the ground state [36], and developed a new method to probe quantum coherence using double-dot structures [37]. An important contribution from technological point of view was our much-argued assertion that even high quality thin thermal oxides contain large (>300 Å) active charge traps[38,39], a conclusion later supported by direct Kelvin-probe studies conducted by IBM researches.

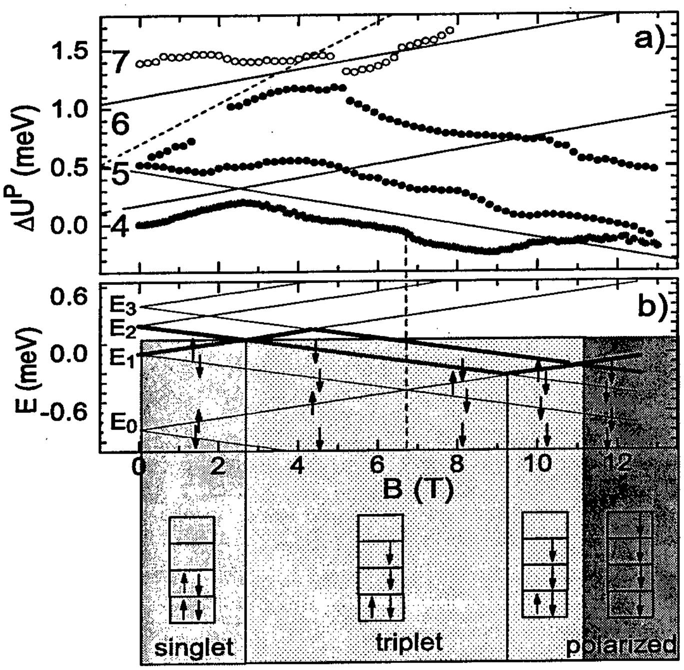


Figure. Direct measurement of the ground state spin configuration of a small Si quantum dot . a) Shift of the ground state energy in a dot containing 4, 5, 6, and 7 electrons as a function of magnetic field *B*. Solid and dashed lines have slopes 1/2 and 3/2 $g^*\mu_B$ (Zeeman shift) respectively. b) Schematic evolution of single-particle energy levels, assuming only the Zeeman level splitting. Spin orientation of each level is shown schematically with an arrow. Singlet, triplet and fully polarized configurations of the ground state with 4 electrons are outlined with colors, red arrow represents polarization of the tunnelling electron.

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H. Yin, K.D. Hobart, F.J. Kub, S.R. Shieh, T.S. Duffy, J.C. Sturm, "Strain partition of Si/SiGe and SiO2/SiGe on compliant substrates," Appl. Phys. Lett. 82 (22) pp. 3853 – 3855 (2003).

H. Yin, R. Huang, K.D. Hobart, J. Liang, Z. Suo, S.R. Shieh, T.S. Duffy, F.J. Kub, and J.C. Sturm, "Buckling suppression of SiGe islands on compliant substrates," Journal of Applied Physics, 94, p. 6875 (2003).

A. C. Johnson, C. M. Marcus, M. P. Hanson, A. C. Gossard, "Coulomb-Modified Fano Resonance in a One-Lead Quantum Dot," submitted to *Phys Rev. Lett.*, (cond-mat/0312571) (2003).

L. DiCarlo, H. J. Lynch, A. C. Johnson, L. I. Childress, K. Crockett, C. M. Marcus, M. P. Hanson, A. C. Gossard, "Differential Charge Sensing and Charge Delocalization in a Tunable Double Quantum Dot," submitted to *Phys Rev. Lett.*, (cond-mat/0311308) (2003).

Wei Wu, Jian Gu, Haixiong Ge, Christopher Keimel, and Stephen Chou, "Room-temperature Si single-electron memory fabricated by nanoimprint lithography," *Applied Physics Letters,* 83 (11), 2268-2270, Sept. 15, 2003

X.-Z. Bo, L.P. Rokhinson, and J. C. Sturm, "SiGe Single-Hole Transistor Fabricated by AFM Oxidation and Epitaxial Regrowth", Tech. Dig. Third International Conference on SiGe(C) Epitaxy and Heterostructures III, pp. 129-130 (2003) .

C. Gustin, S. Faniel, B. Hackens, E.P. DePoortere, M. Shayegan, and V. Bayot, "Evidence for Universal Conductance Fluctuations in an Open Quantum Dot under a Strictly Parallel Magnetic Field," Physica **E 17**, 154-155 (2003).

E.A. Shaner and S.A. Lyon, "Picosecond electrical excitation of a two-dimensional electron gas," invited SPIE presentation at Photonics West (Jan. 2004).

Haizhou Yin, R.L. Peterson, K.D. Hobart, S.R. Shieh, T.S. Duffy, and J.C. Sturm, " High Ge content (~0.6) relaxed SiGe layers by compliant substrates approaches," Proc. Symp. Mat. Res. Soc. vol. 768, pp. 15-19 (2003).

H. Yin, K.D. Hobart, R.L. Peterson, S.R. Shieh, T.S. Duffy, and J.C. Sturm, "Strained-Si-on-Insulator MOSFETs without Relaxed SiGe Buffer Layer", Tech. Dig. Third International Conference on SiGe(C) Epitaxy and Hetereostructures, pp. 181-183 (2003).

X.-Z. Bo, L. P. Rokhinson, D. C. Tsui, and J. C. Sturm, "SiGe single-hole transistor fabricated by AFM oxidation and epitaxial regrowth", Tech. Dig. Device Research Conference, pp.129-130 (2003).

H. Yin, K.D. Hobart, S.R. Shieh, T.S. Duffy, and J.C. Sturm, "Strain partition of Si/SiGe and SiO2/SiGe islands on compliant oxide", Ext. Abs. 45th Electronic Materials Conference, p. 38 (2003).

H. Yin, K.D. Hobart, R.L. Peterson, S.R. Shieh, T. FETs on insulator without SiGe buffers," Tech. Dig. S. Duffy, F.J. Sub and J. C Sturm, "Fully depleated Strained Si-MOS"

S.Y. Chou, L. Koecher, L. Kong, Hua Tan, Invited Talk, "Multilevel Sub-10 nm Nanoimprint Lithography Tools, Microlithography and Advanced Microelectronics Micromanufacturing 2003 (Emerging Lithographic Technologies), Santa Clara, CA, Feb. 24-26, 2003.

S.Y. Chou, Invited Talk, "Nanoimprint Lithography – An Engine for Low-Cost and High Throughput Nanomanufacturing," NSF Workshop on Nanoscale Mechanical Engineering, Arlington, VA, June 15-16, 2003.

S.Y. Chou, Invited Talk, "Impact of Nanoimprint Lithography to Device Development," Device Research Conference, Salt Lake City, UT, June 21-23, 2003.

L. DiCarlo, H. J. Lynch, A. C. Johnson, L. I. Childress, K. Crockett, C. M. Marcus, M. P. Hanson, and A. C. Gossard, *Differential Charge Sensing and Charge Delocalization in a Tunable Double Quantum Dot,* Phys. Rev Lett. vol 92, art. 226801 (2004).

H.Z. Yin, K.D. Hobart, F.J. Kub, and J.C. Sturm, "High-germanium-content SiGe islands formed on compliant oxide by SiGe oxidation," App. Phys. Lett. vol. 84, pp. 3624-3626 (2004)

V.C. Unrefereed Conference Publications.

Stergios J. Papadakis, E. P. De Poortere, H. C. Manoharan, M. Shayegan (Princeton University, Department of Electrical Engineering), R. Winkler (Institut Für Technische Physik III, Universität Erlangen-Nürnberg), [LC30.02] *The role of spin-splitting in the metallic behavior of a two-dimensional hole gas in GaAs,* APS Conference, March, 1999.

M Switkes, C M Marcus (Department of Physics, Stanford University), K Kampman, A C Gossard (Materials Department, University of California Santa Barbara), [QC21.01] *Adiabatic Quantum Electron Pumping,* APS Conference, March, 1999

Fei Zhou, Boris Altshuler (Physics Department, Princeton University and NEC Research Institute, Princeton), Boris Spivak (Physics Department, University of Washington, [QC21.10] *Mesoscopic machanism of adiabatic charge transport,* APS Conference, March, 1999.

J. A. Folk (Dept of Physics, Stanford University), D. R. Stewart (Dept of Applied Physics, Stanford University), C. M. Marcus (Dept of Physics, Stanford University), C. I. Duruoz, J. S. Harris Jr. (Dept of Electrical Engineering, Stanford University), [EC21.01] *Dephasing in Nearly-Isolated Quantum Dots*, APS Conference, March, 1999.

L. P. Rokhinson, C. J. Chen, D. C. Tsui (Princeton University), G. A. Vawter (Sandia National Laboratories), K. K. Choi (U. S. Army Research Laboratory), [VC22.10] *Quantum Grid Infrared Photodetectors,* APS Conference, March, 1999.

M. Hilke, D. Shahar, S.H. Song, D.C. Tsui (Princeton University), Y.H. Xie (Bell Laboratories), [YC16.07] *Universality and the Global Phase Diagram,* APS Conference, March, 1999.

D. Wasserman, S.A. Lyon (Princeton University, Department of Electrical Engineering, Princeton, NJ, 08544), [V28.010] *Mid-Infrared Emission from Self-Assembled InAs Quantum Dot Structures in Resonant Tunneling Devices,* APS Conference, March, 2000.

Ady Stern (Weizmann Institute), Bertrand I. Halperin (Harvard), Yuval Oreg (Harvard, Weizmann Institute), Jan-Hein Cremers, Charles Marcus, Joshua Folk (Harvard), [N29.013] *Spin orbit effects in a GaAs quantum dot in a parallel magnetic field,* APS Conference, March, 2001.

Karsten Held (Princeton University; NECI Princeton), Igor L. Aleiner (SUNY at Stony Brook), Boris L. Altshuler (Princeton University; NECI Princeton), [L33.016] *Effect of adiabatic noise on the conductance of a nearly isolated quantum dot*, APS Conference, March, 2001.

J.A. Folk, R.M. Potok, A.C. Johnson, S.M. Cronenwett, C.M. Marcus (Harvard University), W.G. van der Wiel, L.P. Kouwenhoven (Delft University), [C25.004] *Gate-Controlled Spin Transport Through GaAs Quantum Dots,* APS Conference, March, 2001.

Jeng-Bang Yau, E. P. De Poortere, M. Shayegan (Department of Electrical Engineering, Princeton University), [G25.001] *Aharonov-Bohm oscillations in (311)A GaAs 2D holes,* APS Conference, March, 2001.

Sibel P. Bayrakci, N.P. Ong, S.J. Papadakis, M. Shayegan, D.C. Tsui (Princeton University), [V25.005] *Cyclotron resonance in 2D electron and hole gases at low frequencies (0.5 - 110 GHzk),* APS Conference, March, 2001.

D. M. Zumbuhl, J. A. Folk, J. B. Miller, S. K. Watson, C. M. Marcus (Harvard University), S. R. Patel, C. I. Duruoz, Jr. Harris (Stanford University), [C25.006] *Spin Effects in Transport Through Open Quantum Dots,* APS Conference, March, 2001.

J. M. Taylor, J. A. Folk, A. A. Houck, C. M. Marcus, M. D. Lukin (Physics Department, Harvard University, Cambridge, MA), [J19.006] *Coherent spin manipulation and quantum computation in double-dot molecules,* APS Conference, March, 2002.

H.J. Lynch, S.M. Cronenwett, C.M. Marcus (Harvard University), L.P. Kouwenhoven (Delft University), V. Umansky (Weizmann Institute), [F24.015] *Spin Effects and `0.7 Structure' in Quantum Point Contacts,* APS Conference, March, 2002.

D. M. Zumbühl, J. B. Miller, C. M. Marcus (Harvard University), A. C. Gossard (University of California, Santa Barbara), [J19.005] *Weak Antilocalization in Open Quantum Dots and the Effect of Parallel Magnetic Fields*, APS Conference, March 2002.

Eli Eisenberg, Karsten Held, Boris L. Altshuler (Dept. of Physics, Princeton University, Princeton, NJ 08544 and NEC Research Institute, 4 Independence Way, Princeton, NJ 08540), [F23.001] *Dephasing in closed quantum dots,* APS Conference, March, 2002.

D. Wasserman, S.A. Lyon (Princeton University), M. Hadjipanayi, J.F. Ryan (Oxford University), [S23.004] *InAs Growth on [110] GaAs: Will Quantum Dots Form?,* APS Conference, March, 2003.

H. J. Lynch, L. DiCarlo, L. I. Childress, N. J. Craig, M. D. Lukin, C. M. Marcus (Department of Physics, Harvard University), M. P. Hanson, A. C. Gossard (Department of Electrical and Computer Engineering, University of California, Santa Barbara), [Y19.012] *Capacitive Sensing of Localized Charge in a Double Quantum Dot System,* APS Conference, March, 2003.

Babur Habib, Emanuel Tutuc, Sorin Melinte, Daniel Wasserman, Stephen Lyon, Mansour Shayegan (Princeton University), Roland Winkler (Institut fuer Technische Physik III, Universitaet Erlangen-Nuernberg), [H23.010] *Spin-orbit interaction-induced spin-splitting in GaAs (100) 2D holes,* APS Conference, March, 2003.

R. M. Potok, J. A. Folk, C. M. Marcus (Harvard University), V. Umansky (Weizmann Institute), [P22.001] *Spin states and polarized current emission from Coulomb blockaded quantum dots,* APS Conference, March, 2003

Charles Marcus (Department of Physics, Harvard University), [A7.005*] Gate-Controlled Spin-Orbit Effects in a 2D Electron Gas and in Quantum Dots,* APS Conference, March, 2003.

O. Gunawan, E. P. De Poortere, Y. P. Shkolnikov, K. Vakili, E. Tutuc, M. Shayegan (Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544), J. B. Yau (313 Becton Center, Applied Physics, Yale University), [A23.005] *Ballistic transport in AlAs 2D electrons,* APS Conference, March, 2003.

Mansour Shayegan (Department of Electrical Enigineering, Princeton University, Princeton, NJ 08544), [A7.002] *Aharonov-Bohm oscillations with spin: evidence for Berry's phase,* APS Conference, March 2003.

E.A. Shaner, S.A. Lyon (Princeton University Electrical Engineering Dept*),* [A23.003] *Picosecond Time Resolved Transverse Magnetic Focusing in an AlGaAs/GaAs 2DEG,* APS Conference, March, 2003.

A. C. Johnson, C. M. Marcus (Harvard University), M. P. Hanson, A. C. Gossard (University of California, Santa Barbara), [B22.006] *Phase Measurements in a Quantum Dot with Tunable Fano Resonances,* APS Conference, March, 2003.

D. M. Zumbühl, C. M. Marcus (Department of Physics, Harvard University), M. P. Hanson, A. C. Gossard (Department of Electrical and Computer Engineering, University of California, Santa Barbara), [H37.002] *Singlet and Triplet States and the Kondo Effect in a Few Electron Quantum Dot,* APS Conference, March, 2004.

B. Habib, E. Tutuc, S. Melinte, M. Shayegan, D. Wasserman, S. Lyon (Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA), R. Winkler (Institut für Festkörperphysik, Universität Hannover, Appelstr. 2, D-30167 Hannover, Germany), [J15.012] *Anomalous Rashba spin splitting in GaAs two-dimensional hole systems,* APS Conference, March, 2004.

N.J. Craig, J.M. Taylor, E.A. Lester, C.M. Marcus (Department of Physics, Harvard University), M.P. Hanson, A.C. Gossard (Materials Department, University of California, Santa Barbara), [H37.001] *Non-local spin control in a coupled quantum dot system: A tunable RKKY-like interaction,* APS Conference, March, 2004.

A.C. Johnson, C.M. Marcus (Harvard University), M.P. Hanson, A.C. Gossard (University of California, Santa Barbara), [Y37.009] *Latched Detection of Excited States in an Isolated Double Quantum Dot,* APS Conference, March, 2004.

R. Winkler (Institut für Festkörperphysik, Universität Hannover, Germany), E. Tutuc, S. Melinte, M. Shayegan, D. Wasserman, S.~A. Lyon (Department of Electrical Engineering, Princeton University), *[W11.007]* Spin Polarization of Two-Dimensional Hole Systems, APS Conference, March, 2004.

Y. P. Shkolnikov, K. Vakili, M. Shayegan (Department of Electrical Engineering, Princeton University, Princeton NJ 08544), E. P. De Poortere (Department of Physics, Columbia University, New York NY 10027), [W11.013] *Strain dependence of spin and valley polarization in AlAs 2D electrons*, APS Conference, March, 2004.

Leonid P. Rokhinson (Purdue University), Y.B. Lyanda-Geller (NRL), D.C. Tsui (Princeton University), L.N. Pfeiffer, K.W. West (Bell Laboratories), [B37.009] *g-factors in p-GaAs quantum point contacts,* APS Conference, March, 2004.

D. Technical Reports

1999 Annual Report submitted January 2000
2000 Annual Report submitted January 2000
2001 Annual Report submitted April 2002
2002 Annual Report submitted May 2003
2003 Annual Report submitted May 2004

VI. Personnel

Michael D. Austin: Still at Princeton in 2004
Baitine, Alexander
Berkovitz, Richard
Bishop, Nathanial – Princeton University
Bo, Xiang Zheng – Dupont, Wilmington, DE
Chen, Lei
De Poortere, Etienne P. – Post Doc at Columbia University
Eisenderg, Eli – Tel Aviv University
Folk, Joshua -Assistant Professor University of British Columbia
Gray, John - Intel
Gunawan, Oki – Princeton University
Habib, Babur – Princeton University
Held, Karsten - Max Planck Institute
Johnson, Alex – Still a graduate student at Harvard with Professor Marcus
Khavine, Iouri– Returned to Russia
Kurland, L
Lee, Audrey – Switched Fields to Environmental Policy
Lerner, Igor – University of Birmingham, UK
Li, Chunqiang Princeton University
Ora, John E.
Papadakis, Stergios – Applied Physics Lab, Johns Hopkins
Peterson, Rebecca – Graduate Student, Princeton University
Rokhinson, Leonid (since Sept, 2002, Ass't. Prof., Dep't. of Physics, Purdue University
Shaner. Eric – Sandia National Labs
Shekar, Kiran – Left Grad School
Shutenko, Timur
Stewart, Eric – Northrop Grumann
Tan, Tat – Princeton University
Tutuc, Emmanuel – IBM Research, Yorktown Heights
Ussishkin, Iddo - University of Minnesota
Venkataraman, Venkatakrishnan – Indian Institute of Science, Bangladesh, India
Wang, Z.
Wasserman, Daniel – Post Doc, Princeton University working with Professor Gmachl
Xie, Zhijian – Agere Technologies
Yau, Jeng-Bang graduated in September 2002, now a postdoc at Yale University
Yau, Tony – Yale University
Yin, Haizhou – IBM Yorktown
Yu Zhaoning – Hewlett Packard
Yusbashyan, Emil – Rutgers University
Zhou, Fei – University of Oxford
Zumbuhl, Dominik – Now a post doc with Professor Marc Kastner at MIT

VII. Inventions, Patents and Filings

1998
None

1999
None

2000
None

2001
01-1783-1 Germanium Epitaxy Layer on Silicon Substrate Using Compliant Layer
01-1784-1 Defect-Free Continuous Relaxed SiGe Layer by Epitaxial Growth on Islands

2002
None

2003
US. Patent #6573737 "Method and apparatus for non-contact measurement of electrical properties of materials" S.A. Lyon, E.A. Shaner, and I.E. Trofimov.

03-2050-1 Defect-Free Strain Engineering on Compliant Substrates

2004
None

VIII. Honors and Awards

1998
None

1999
Prof. Stephen Chou, IEEE Fellow 1999.
Prof. Mansour Shayegan, APS Fellow, 1999
Prof. Daniel C. Tsui, Honorary Ph.D., University of Chicago 1999.
Ms. Min Yang: Best Student Paper Award (co-authors: M.S. Carroll and J.C. Stunn); "Doped vs. unooped SiGeC layers in sub-l00 nrn vertical p-channel MOSFEf's,"Int. Conf. Silicon Epitaxy and Heterostructures. Miyagi, Japan (September, 1999).
Prof. Charles Marcus moved to Harvard University to participate in the construction of a new research center, the "Center for Imaging and Mesoscopic Systems" which includes a new building.

2000:
Professor James C. Sturm, IEEE Fellow. 2000

2001:
J. C. Sturm, Symposium Organizer "Materials Issues in Novel Silicon-Based Technology," Materials Research Society Meeting, Boston, Massachusetts, November 2001.

S.J. Papadakis, E.P. De Poortere, M. Shayegan, and R. Winkler, *"Spin-splitting in GaAs 2D Holes,"* (invited paper) in Proc. 11th International Winterschool on New Developments in Solid State Physics, Mauterndorf, Austria Physica **E 9**, 31-39 (2001)

2002:
Boris Altshuler was elected a member of the National Academy of Sciences Was awarded the Oliver Buckley Prize of American Physical Society

Mansour Shayegan was awarded one of Princeton University's first "Graduate Mentoring Awards" in Spring 2002

James Sturm served as Interim Dean of the School of Engineering and Applied Science, Princeton University, July 2002 – January 2003.

Joshua Folk (was Harvard student on project): Pappalardo Post-Doctoral Fellowship, MIT.

2002: Work of Prof. Shayegan for observation of Berry's phase in spin-orbit dependent transport written up in "Physics Portal" of the Nature journal on March 26, 2002, in the Virtual Journal of Nanoscale Science & Technology on April 12, 2002, and in the "Science's Compass" section of the Science magazine on September 6, 2002 [J. Anandan, Science 297, 1656 (2002)].

2003
J.C. Sturm, re-elected president of Device Research Conference.
J.C.Sturm, named Director of newly formed Princeton Research Institute for the Science and Technology of Materials
Alex Johnson: Harvard Dept. of Physics Merit Fellowship

2004
James C. Sturm awarded President's distinguished Teaching Award, Princeton University

Prof. Stephen Chou awarded IEEE Cledo Brunetti Award for his invention of groundbreaking techniques in nanotechnology.